AN ASSESSMENT OF ATMOSPHERIC SCIENCE RESEARCH OPPORTUNITIES ABOARD NASA'S SOFIA ASTRONOMICAL OBSERVATORY

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ABSTRACT

Between 1981 and 1994 our group flew more than fifty piggyback flights aboard NASA's Kuiper Airborne Observatory (KAO), a modified C-141 aircraft that was the precursor to SOFIA. The focus of that work was the development and application of innovative techniques for the precise measurement of the vanishingly small quantities (mixing ratios on the order of 10^{-20}) of radon gas typically found in the middle and upper troposphere. Our piggyback flights aboard the Kuiper Observatory not only allowed us to make some surprising discoveries about the actual (as opposed to the supposed) distribution and transport of radon (and other trace gases) in the mid and upper troposphere, and to acquire a statistically significant set of high-quality free tropo-spheric radon measurements that still finds frequent use in the modeling community, but also to develop the automated radon instrument that was successfully flown aboard a NASA ER-2 high altitude research aircraft.

Should SOFIA made available to similar atmospheric science piggyback experiments? I believe the answer is yes. Although on the one hand the more restrictive operating constraints anticipated for SOFIA would make the necessary pre-flight preparations more costly and time-consuming, the drivers—e.g., the scientific benefits to be gained, considerations of cost-effectiveness, the success of the related European MOZAIC and CARIBIC programs, and the projected reductions, in today's research climate, of the number of alternative flight opportunities—are proportionately stronger. The difference is that a community effort would be required, in order to put in place aboard SOFIA the infrastructure necessary (reinforced window ports, sampling inlets, electrical circuits, etc.) thus reducing to an acceptable level the costs and time required for the installation of individual future experiments.

INTRODUCTION

SOFIA (Stratospheric Observatory for Infrared Astronomy), a joint NASA/DLR project, is scheduled to become operational in the fall of 2005. Like its precursor, NASA's Kuiper Airborne Observatory (a modified Lockheed C-141 aircraft) SOFIA (a modified Boeing 747) will carry a large infrared telescope and log many hours of flight time in the upper troposphere and lower stratosphere, in order to get above the tropospheric dust and water vapor that would interfere with its astronomical observations. While the primary mission of SOFIA, as for the Kuiper Observatory (KAO), will be astronomy, as was the case aboard the KAO there will also be some unused space aboard SOFIA that could be made available to piggybackers.

As part of the process of assessing this possibility a meeting (the SOFIA Upper Deck Science Opportunities Workshop, June 22-23, 2004) was recently held at the NASA Ames Research Center. Organized by Peter Jenniskens and Hansjuerg Jost (c.f. Jenniskens, et al., 2004) it brought together several dozen scientists from the United States and Europe for two days of presentations and discussion.

This report is based on my own oral presentation at that meeting, which centered upon a review of the atmospheric science experiments my group had carried out piggybacking aboard the KAO in the 1980s and 90s, but also incorporates elements of some of the other presentations and discussion at that meeting. I have provided a fairly detailed summary of our three KAO projects as those projects illustrate not only the results that were obtained, but also the kinds of technical problems that must be addressed and overcome in any eventual atmospheric science piggyback experiments aboard SOFIA, and the procedures that were followed in formulating, gaining approval for flight, and carrying out those projects.

I also wish to point up that these projects, which in the end were so fruitful, were at the outset both speculative and (at least in the case of the initial project) relatively underfunded. Looking back, it's not clear that we could have obtained the significantly higher level of funding that would have been required for that first project had, absent the opportunity presented by the KAO, we had had to develop our instrumentation and obtain our initial results flying aboard a dedicated atmospheric research aircraft such as the NASA Lear Jet or CV-990. Thus another purpose of this report is to advocate that similar opportunities be made available aboard SOFIA.

To this end Section 2 of this report reviews the scientific rationale, experimental installations, operations and results of the three projects my group carried out aboard the KAO; Section 3 discusses some of the atmospheric science piggyback experiments carried out in the past aboard other aircraft (e.g., GASP, MOZAIC, CARIBIC) and the scientific rationale for related (and un-related) programs aboard SOFIA. Finally, Section 4 discusses the operational and procedural environment aboard SOFIA, and outlines an approach which would make atmospheric science piggybacking aboard this aircraft both feasible and fruitful.

THREE SUCCESSFUL ATMOSPHERIC SCIENCE PROJECTS ABOARD THE KAO

Project 1. The KAO mid-latitude radon intrusion experiment

The KAO mid-latitude radon intrusion experiment—scientific rationale. Beginning with my Ph.D. thesis (Formation Mechanism of the Background Stratospheric Aerosol) I have had an ongoing interest in stratosphere-troposphere exchange, or, more precisely, the movement of tropospheric air (and its burden of trace constituents) into the stratosphere. While most of this movement occurs across the tropical tropopause, it had been postulated (Danielsen, 1968) that a lesser, though not insignificant, movement of tropospheric air into the stratosphere might occur at mid-latitudes, in conjunction with tropopause folding. As it happens the normal operations of the Kuiper Airborne Observatory resulted in its frequently flying in this region of the atmosphere; this fact, together with my (and Ed Danielsen's) presence at Moffett Field, where the KAO was based, and my prior acquaintance with the French research group that had pioneered the use of radon as a tracer for tropospheric air masses (Lambert and Polian, 1968) led to formation, in December, 1981, of an ad hoc French-SUNYA-NASA Ames project to make radon measurements aboard the KAO, with the goal of looking for traces of radon in the lower midlatitude stratosphere. Such a finding would be compelling evidence for the occurrence of intrusions, at mid-latitudes, of tropospheric air into the stratosphere.

Radon (^{222}Rn) is a radioactive inert gas which enters the atmosphere at ground level, where it is formed by the radioactive decay of the trace quantities of uranium found naturally in rocks and soils. Because it is inert, and not scavenged by precipitation, once in the atmosphere radon's only significant removal mechanism is its own radioactive decay, which occurs with a half-life of 3.8 days. In the pioneering work (cited above) of the French group radon served as an unambiguous tracer for the presence of continental air intrusions in remote oceanic regions; in the KAO project outlined here it would serve as an equally unambiguous tracer for the presence in the lower stratosphere of air of recent tropospheric origin. The problem was how to make a sufficiently sensitive and accurate radon measurement aboard a fast-moving, high-flying aircraft.

The KAO mid-latitude radon intrusion experiment—Instrumental approach to the measurement. Broadly speaking, there were (and are still) two ways in which radon can be measured from an aircraft. The first is relatively straightforward—air samples are collected in flight, and then returned to a ground-based laboratory for a post-flight analysis of their radon content. The second involves not the collection of radon itself, but rather its short-lived daughter products. These are produced as radon gas decays, and in both the troposphere and the stratosphere are in equilibrium with their parent radon. Thus, by sampling and analyzing the ambient concentration of the short-lived radon daughters, the ambient concentration of radon gas can be determined. However as these short-lived progeny have a relatively short (~40 minute) half-life, their measurement must be carried out in flight, starting within a few minutes of their collection.

Although both the whole air and the radon daughter approaches were potentially suitable—i.e., equipment could be built using either approach that would have the requisite sensitivity for the experiment we had in mind—and each had its own advantages and drawbacks, the short-lived daughter approach was chosen for this particular project because our analyses indicated that a radon daughter instrument with the necessary sensitivity could be built and installed aboard the KAO faster, and at a substantially lower cost than could the instrumentation needed for the ambient air sample method. Even so, some formidable problems had to be solved in order to build and install the necessary equipment. (We used the whole air approach in a second flight campaign aboard the KAO, as that approach was best suited for the goals of that project. This second campaign is outlined in Section 2C of this report.)

The radon daughter measurement is a two stage process: acquisition of a sample; followed by analysis of the sample's radon daughter content. The basic elements of sample acquisition are a suitable sampling inlet, a filter on which to trap and collect the radon daughters, and a pump to move air through the system. The on-board sample analysis requires a detector system (located in the rear portion of the KAO cabin) together with a control system to operate the pump, and keep track of the radon daughter analysis. As discussed below, the critical problems in the experiment were provision of a suitable sample inlet, and of a noise-free detector system.

Almost immediately after their formation—in a matter of a few seconds—the short-lived radon daughters produced by radon decay are irreversibly scavenged by sub-micron-sized particles of the ambient atmospheric aerosol. Thus the radon daughter collection process involves obtaining an unbiased (and sufficiently large) sample of the ambient sub-micron aerosol population. The difficulty here is that even sub-micron-sized aerosol particles have an appreciable inertia relative to that of the air molecules in which they are suspended; thus for representative sampling abrupt changes in airflow direction must be avoided. Therefore the external inlet—i.e., the inlet on the fuselage of the aircraft by means of which the ambient aerosol particles are collected—has to meet two criteria: that the velocity of the ambient air entering the sample inlet be within a few percent of the <u>velocity</u> of the local free air stream at the point where the inlet is located, and that the inlet be in precise alignment with the <u>direction</u> of the local free air stream.

The jargon for this condition is that of an *isokinetic* collection, and although a description of our experimental installation, as well as of the physics underlying the radon daughter method may be found in the paper describing this project (Kritz et al., 1990) I mention this here because these same considerations apply to *any* accurate and representative of ambient aerosol products from an aircraft, including any such collections eventually anticipated aboard SOFIA. (A no less important problem, which space considerations prevent discussing here, is that the inevitable losses of aerosol particles *within* the sampling inlet and ducting be tolerably small and relatively invariant.)

In this project we were very fortunate in that a group leader at an internationally recognized aircraft instrumentation company, who we had approached for advice, took an interest in our problem (which was closely related to another inlet problem that he was already working on) and offered to modify that design and make available at cost a suitable inlet assembly for use in our project. This was an unforeseen stroke of good luck, and contributed significantly to the eventual success of our experiment.

Another essential element of our experiment was the availability of a low-noise detection system. As mentioned earlier, the radon daughter products collected on the filter are themselves are subject to radioactive decay, with a mean half-life on the order of 40 minutes. As discussed in Kritz et al. (1990)

and by Lambert and Polian (1968) this decay is accompanied by the emission of both gamma and alpha particles, so that the ambient radon concentration can be determined on the basis of the gamma or alpha activity present on the filter. However while gamma and alpha detectors are a common feature of many radiochemical laboratories, the problem was that the ambient cosmic ray flux, which acts to increase the detector background noise level, increases significantly with altitude, as the mass of the overlying atmosphere diminishes. Here a key element in our planning and preparations was that Jean-Claude Le Roulley, our lead French collaborator, had had considerable experience and success in designing and building sensitive low background alpha detectors for use aboard high altitude balloons.

Thus it appeared that the two most critical instrument development problems—the design of a suitable inlet, and the availability of a suitable detector—could be overcome.

Fig. 1. General view of the KAO, showing the location of our sampling inlet.

The KAO mid-latitude radon intrusion experiment—gaining approval for installation. We had at this point already approached the KAO operations office with an outline of the scientific goals of our proposed project, and a rough description of the type of equipment that we would need to fly in order to make the radon measurement. Having obtained approval to proceed to the next stage (these procedures, as well as the facilities available and the norms for experiments, astronomical or otherwise, to be followed aboard the KAO were set out in the *Kuiper Airborne Observatory Investigator's Handbook*), we now returned to KAO operations with some preliminary design sketches of the aerosol inlet, which we had proposed mounting in place of the small window on the right hand forward emergency exit of the aircraft. (The prior KAO operations review of our experiment had approved the eventual installation of the inlet at that location, provided that its design was such that its presence would not prevent the use of the door in an emergency evacuation.) We also provided some specific information about the type of pump we would need, the types of hoses that would run between the pump and the inlet, and the size and weight of the detector/control system that would be located in the rear of the cabin.

Following this second review the next step was to perform an aerodynamic analysis of the proposed inlet probe design under various conditions of normal and abnormal aircraft operation, in order to determine the aerodynamic forces that the inlet itself would have to withstand, as well as the magnitude of the forces that would be transmitted to the airframe—or, more precisely, the emergency door structure—and then to design bracing to fit within the emergency door structure, to carry these additional forces. These tasks were performed on a reimbursable (by our project!) basis by an on-site contractor at Moffett Field that over a period of years had worked with the Ames Research Center Flight Operations Directorate on similar problems related to experimental modifications of NASA's local fleet of aerodynamic and scientific research aircraft.

At this point we carried out an important interim experiment aboard the KAO. Working with KAO operations, and with one of the aerodynamics research groups at NASA Ames, we ar-ranged for the temporary installation of a sort of small wind vane on the emergency exit door, at the precise location where our inlet probe would eventually be installed, and to fly it on a regular astronomy research flight. This vane, as well as our inlet assembly as it was eventually installed upon the aircraft, are shown in Figures 1, 2 and 3.

Fig. 2. The temporary windvane as installed at our sampling location.

Fig. 3. Closeup view of our sampling inlet.

The electronic output of the wind vane provided not only the direction (relative to the horizontal reference plane of the fuselage) of the local wind field at the inlet location, but also revealed the extent to which the local flow direction varied during flight, for as fuel was burned off the angle of attack of the aircraft changed. This showed that the change of local airflow direction at the inlet location over the course of a flight fell within a range that would still permit isokinetic operation of the inlet, and also allowed us to establish the optimum angle for its orientation. As may be seen in Figure 3 this was several degrees below the fuselage's horizontal reference plane, reflecting the fact that the C-141 normally flys in a slightly "nose up" configuration.

We then returned for a third, formal review. The aerodynamic lift/drag calculations were presented both orally and in the form of a written report, along with detailed drawings of the proposed inlet probe assembly, the bracing to be fabricated and installed in the emergency door, the pump module, as well as the pump control module, the detector and the data acquisition system, which was to be installed in a investigator's equipment rack in the rear of the cabin. After review (and several modifications) the drawings and calculations were approved, so that we could go ahead with the fabrication of the inlet probe assembly, place the order for the pump, and put in place funding to cover the cost of the emergency door bracing, which was fabricated and installed by the Metal Fabrication Shop at the Ames Research Center—the shop where a wide range of aircraft modification work of this sort had for years been carried out by the expert personnel of that organization, under the supervision of on-site NASA airworthiness inspectors.

The KAO mid-latitude radon intrusion experiment—final approval, and integration. As the various components of our experiment arrived at Moffett Field they were inspected and then assembled into the modules (which in turn were re-inspected) that were to be installed aboard the KAO. An interim step in this process involved a temporary positioning of our pump close to its eventual location aboard the aircraft, and running it on the ground to verify that it did not generate any electrical or mechanical noise or interference that might affect the astronomical equipment aboard the aircraft. Once this was done the pump was installed under the false floor adjacent to the emergency door, power and control cables were run back to the control/analysis rack in the rear portion of the cabin, and flexible hoses (with quick disconnect fittings) were run from the pump to the point where they would connect with our sampling inlet. (While the system was not elaborate, in the course of adapting the KAO to carry a telescope several "extra" 120 volt single phase and 208 volt three phase (400Hz) circuits had been installed in the rear portion of the aircraft cabin—one of which we used to power our experiment. Also, because the C-141 had originally been built as a cargo aircraft, "hard points" to secure equipment were present throughout the cabin.) Shortly thereafter the inlet assembly was installed on the emergency door, and we took advantage of a daytime pilot proficiency flight to perform an initial system shakedown, and to verify that it did not pose any problems to the aircraft's safe operation. Several days thereafter, in the spring of 1983, we made our first radon data acquisition flight.

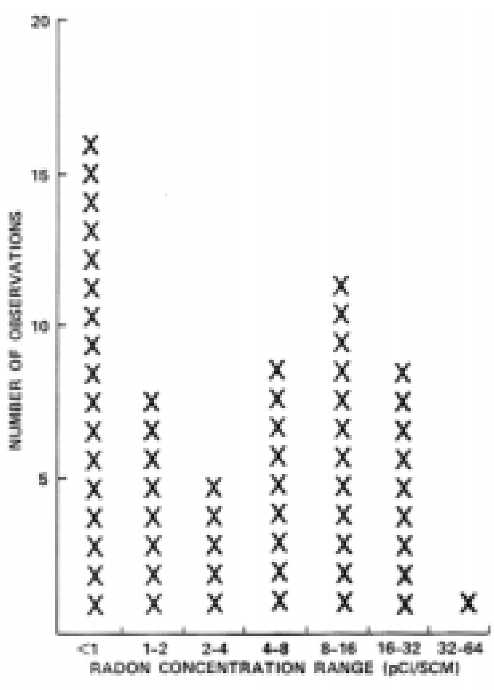

Fig. 4. Frequency distribution plot of the 61 upper tropospheric radon measurements reported in Kritz et al. (1990).

The KAO mid-latitude radon intrusion experiment—scientific results. Briefly stated, the scientific returns from this experiment were far greater than we had anticipated, or even hoped for. Although in the event the KAO did not spend as much time flying in the lower stratosphere as anticipated, its flight patterns did permit us to make a great many radon measurements in the upper troposphere, a region of the atmosphere where only a very small number of prior radon measurements had been made (c.f. Moore, et al., 1972).

In the summers of 1983 and 1984 we made 13 flights aboard the KAO, and obtained 61 radon measurements in the mid-latitude upper troposphere. To our surprise those measurements did not show the "expected" behavior, which would have been to cluster around radon activities of zero to 1 or 2 picoCuries per standard cubic meter (pCi/scm). Instead their distribution had a distinct bimodal character, with one mode, as expected, falling in the zero to 2 pCi/scm range, and a second mode (see Figure 4), comprising a little more than half of the measurements, centered at approximately 11 pCi/scm!

Air mass trajectory and synoptic analyses, described in detail in the resultant publication (Kritz et al., 1990) revealed that this radon-rich air originated in the Asian boundary layer, ascended in cumulus updrafts, and was rapidly carried eastward over the Pacific, towards Hawaii and California, in the upper tropospheric jet stream. But beyond what this finding revealed about the atmospheric distribution of radon, it was important in a larger sense because it followed that the pollution also present in the Asian boundary layer could also be rapidly transported, in the upper troposphere, across the Pacific to the North American continent.

A second important aspect of this result, and of the upper tropospheric radon abundances revealed by our measurements, was that the global circulation models which were emerging at the time could not account them for. This piqued the interest of several global modeling groups, who worked with us to integrate a radon calculation algorithm into their models, with the goal of using comparisons between the predicted and measured radon distributions in the further development and refinement of the transport portion of their models (e.g. Balkanski et al., 1992.) The application to global model development of this and subsequent radon data sets acquired aboard the KAO continues to this day.

Finally, as discussed later, the success of this project and of our radon measurement technique opened the door for our participation in STEP, NASA's Stratosphere Troposphere Exchange Project.

The KAO mid-latitude radon intrusion experiment—the unique and essential role of the KAO. In retrospect, the success of this, the first of our three projects aboard the KAO, was due to many factors—not the least of which were a lot of hard work, several happy coincidences, and some help from our friends. I also acknowledge with pleasure the relatively small but very welcome and important funding grants provided by the respective Director's Discretionary Funds at the NASA Ames Research Center, and at our French colleague's home laboratory in France. However beyond these important elements, our success stemmed from three factors which were specific to the KAO—and which could also be relevant for similar projects aboard SOFIA.

First, because the KAO was a large aircraft, we did not have to devote a disproportionate effort to reduce the size of our experimental installation. This saved time, reduced costs, and enhanced the sensitivity of our instrumentation.

Second, the management and the operating teams of the KAO were receptive to the potential value of our experiment. While in so doing they did not in any way compromise airworthiness considerations, or the primary astronomical mission of the KAO, their cooperative and positive attitude, and their desire to maximize the total science return from the KAO, greatly facilitated the task of preparing our experiments for flight.

Third, the KAO's frequent flight schedule allowed us first to refine our experimental installation over several initial flights, and then, during the operational phase of the project, to obtain a "dense" data set which not only revealed an unanticipated rapid long-range transport phenomena, but also had a degree of statistical significance which allowed meaningful comparisons with global circulation models.

As mentioned earlier, prior to our work aboard the KAO a number of radon measurements had been made in the lower stratosphere (Moore et al., 1972). But while that was important ground-breaking work, those measurements were widely scattered in space and time, and so were in effect a number of random data snapshots. In contrast the KAO radon measurements, because they were both larger in number and concentrated in one season and region of the atmosphere, revealed an important long-range transport process which was not apparent from the earlier scattered measurements.

Project 2: Reducing the size of the experiment, to permit flight on the ER-2 in NASA's STEP experiment.

At about the same time that we were making our first radon measurements aboard the Kuiper Observatory, NASA's Stratosphere-Troposphere Exchange Project (STEP) was taking shape. A primary goal of that project was to determine the meteorological process or processes governing the movement of tropospheric air across the tropical stratosphere, and the nature of the dehydration process that presumably accompanied this transfer (Danielsen, 1982). Clearly a radon measurement could play an important role in such an experiment, since the observation of a parcel of stratospheric air which was both dry and had an elevated radon content would be compelling evidence for the recent tropospheric provenance of that air, and of the occurrence of a rapid dehydration mechanism accompanying the exchange.

The STEP Tropical Experiment (c.f. Russell et al., 1993) was scheduled for January 1987, and was to be flown aboard a NASA ER-2 high altitude research aircraft. The success of our KAO radon installation had demonstrated the suitability of the radon daughter technique; the question was whether we could build an automated version of the instrument that would meet the severe space and weight constraints imposed by the ER-2 aircraft.

As it happened a suitable automatic filter sampler/filter changing apparatus had already been developed and flown aboard a U-2 aircraft, so that our primary challenge was to radically reduce the size and weight of our KAO detector assembly—without significantly affecting its sensitivity to alpha particles, or its insensitivity to cosmic ray-induced noise. (The detector we flew on the KAO was about the size of an office wastebasket, and weighed approximately 25 kilograms!)

Although we knew of several promising approaches to a smaller and lighter detector design, none of these had actually been proved in flight, or in the high cosmic ray environment typical of the lower stratosphere. The KAO, however, provided us with an ideal platform on which to run comparison tests of several different detector designs, and to make in-flight adjustments to their operating parameters in order to optimize sensitivity and resistance to background noise. In less than six months we had our answers, and as a result were able to reduce the size and weight of the alpha detector assembly by a factor of twenty!. This was the key to the design of our ER-2 instrument, which flew successfully in the 1987 STEP Tropical Experiment—during which air parcels with both high radon and low water content were in fact observed (c.f. Kritz et al. 1993).

Without the instrument development flights on the KAO, I'm not sure we could have done it.

Project 3: The KAO radon profiles experiment.

As mentioned earlier, the results of our mid-latitude radon intrusion experiment (since rebaptised, on the basis of its findings, as the "China Clipper" experiment) aboard the KAO led to a growing interest in such measurements by the atmospheric science modeling community, especially for vertical profiles, which would be particularly helpful in model development and validation. However the radon daughter filter collection instrument used in our initial KAO flight series was not suitable for acquiring vertical radon profiles, as its sample acquisition time was approximately 25 minutes. This led to our writing (as was done for our participation in the STEP project) a formal proposal, this time covering the development of a pumped whole air sampler, which would have a sample acquisition time of 60 to 90 seconds, thus allowing the collection of a ten to twelve sample profile as the KAO climbed to altitude. (See Kritz et al., 1998, for a complete description of the aircraft installation, and of the ground-based laboratory analysis technique.)

A principal advantage of the pumped whole air approach, other than its significantly shorter sample acquisition time, is that an elaborate inlet was not required, since gaseous radon rather than particulate radon daughters was being collected. However a principal disadvantage was that this collection involved pressurizing our (steel) sample cylinders to approximately 100 ATM pressure. This was not in itself an unduly difficult technical problem, and in any case most medium and large sized aircraft already carry pressurized steel cylinders, which are used to supply oxygen in case of need. Nonetheless, installing a new, untried high-pressure system aboard the KAO (or aboard any aircraft, for that matter) clearly required a high level of pre-flight testing and review, and the presence of redundant levels of fail-safe safeguards.

As before, the KAO team worked with our group in the establishment of the necessary design and performance test standards, and while I can personally attest to the fact that there was no relaxation of those standards, I am also pleased to be able to say that their constructive help and positive attitude greatly facilitated the process.

In the summer of 1994 we obtained a set of 11 vertical radon profiles, concentrated in a 60-day period and extending from the boundary layer to 11.2 km. These profiles have been used in two ways: First in the development of the transport components of two global "off-line" chemical transport models(in contrast to global circulation models, which generate hypothetical (though plausible) wind fields, "off-line" models base their wind fields (and hence the transport of the trace species of interest) on observed global wind fields; e.g., those provided by ECMWF. These wind fields are derived for specific actual days, using a combination on synoptic and satellite observations. Thus an output of a chemical transport or "off line" model might be the predicted radon profile at Moffett Field at, say, 05hr00 UT on June 28, 1994—the time, date and location of one of the 11 radon profiles obtained in our 1994 campaign (Kritz et al., 1998; Stockwell et al. 1998).

A second way of using our 1994 KAO radon data set was to group the 11 profiles to obtain a summertime average. While there are limitations to pushing such an average too far, since there are large-scale secular changes in weather patterns (and in the associated radon [and other trace constituent] distributions) from one year to another, still such an average can reveal certain broad aspects of the distribution—such as the "C-shaped" average profile derived from our 11 profiles. Figure 5, below, shows that averaged profile, together with the (diverging) average summertime radon profiles at Moffett Field generated by two global circulation models.

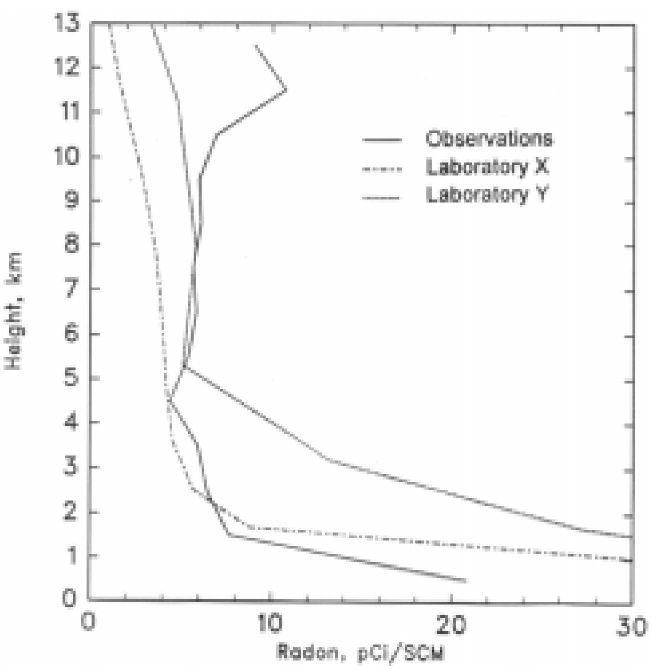

Fig. 5. Average vertical radon profile derived from the 11 summertime profiles of our 1994 flight campaign, compared with GCM output for the same season and region. (Kritz et al., 1998)

(The KAO was decommissioned in 1995. However, thanks to the success of our 1994 KAO campaign we were able to obtain funding to perform a follow-on campaign, aboard a NASA Lear Jet, in the summer of 1996.)

ATMOSPHERIC SCIENCE OPPORTUNITIES ABOARD SOFIA

As I hope the preceding description and discussion of our three KAO piggyback experiments has demonstrated, similar scientific benefits could follow if similar piggybacking opportunities were made available aboard SOFIA. These include the possibility of exploring, at a relatively modest cost, speculative and/or innovative experimental or instrumental concepts, and the possibility of obtaining a large number of systematic observations in one region of the mid and upper troposphere, and in the lower stratosphere.

As Yogi Berra so succinctly put it, "You can observe a lot by looking"—which I take to mean not taking a quick glance or snapshot, or carrying out long-term "monitoring", but rather taking a good long look in a place where you haven't looked before. Unfortunately, when it comes to airborne science, this desire must be tempered by the fact that aircraft time is expensive.

One way around this, which while suited to only a subset of problems is important nonetheless, is piggybacking aboard revenue aircraft—i.e., aboard regular commercial passenger or cargo flights. An early example of this was the GASP program, in which a ~100 kg experimental package was mounted in the avionics bay of several 747 commercial aircraft. While it was unfortunate that programmatic constraints limited the frequency of calibration of the instrumental package, thus severely compromising the utility of the results, still GASP demonstrated the feasibility of the concept.

A similar approach—though with better results—was followed in the MOZAIC program, in which an ~100 kg instrumental package was integrated (again in the avionics bay) aboard several Airbus aircraft, and elaborated upon in the CARIBIC program, in which a larger and heavier instrument package was built into a standard aircraft cargo container flown in the forward position in the cargo bay of several selected Airbus aircraft, which had been modified to provide the container with the necessary power, sampling inlets, and overboard dump lines. (URLs of the websites describing these ongoing programs are given in the reference list.)

While both MOZAIC and CARIBIC have been very successful, piggybacking aboard SOFIA would address a different facet of the problem: First, while the advantages of instrument automation are obvious, when necessary an investigator could accompany his/her instrument aboard SOFIA, to aid in debugging and optimizing performance. As mentioned earlier, the ability to do so aboard the KAO was a great help to us in the development of the automated instrument we eventually flew aboard the ER-2.

A second advantage accruing to SOFIA is frequency of flight and geographical concentration. (While SOFIA may eventually deploy to New Zealand, ~90% of its flying will almost certainly be done out of Moffett Field.) As demonstrated in our "China Clipper" flights (Kritz et al., 1990) the ability to make repeated observations in a limited geographical area and time period revealed both the unexpected bimodal character of the upper tropospheric radon concentrations, as well as the fast trans-oceanic transport process which brought it about. Yogi would suggest that there are other, presently unknown but significant upper tropospheric/lower stratospheric phenomena (involving species other than radon, to be sure!) are out there waiting to be discovered—but that in order to observe them, we're going to have to look!

Another advantage of the frequent observations that would be possible aboard SOFIA is that this would allow the acquisition of statistically significant tropospheric and lower stratospheric seasonal data sets, which in turn would facilitate (indeed permit) meaningful comparisons with the output of the global circulation models which continue to be a mainstay of current climate change and chemical effects modeling efforts.

To return to our original mid-latitude radon intrusion experiment, while that project, and the use of radon measurements to test Danielsen's (1968) hypothesis grew out of informal discussions between three investigators, each working in a different field, the catalysis—the element that enabled those speculations to be transformed into a concrete experiment, which in turn led to a whole series of unanticipated but significant findings—was the possibility of piggybacking aboard the KAO. It would be all to the good if that possibility continued aboard SOFIA.

TOWARDS THE FUTURE--PIGGYBACKING ABOARD SOFIA

An approach to atmospheric science piggybacking aboard SOFIA.

Broadly speaking, any eventual atmospheric science experiments aboard SOFIA will require three things—hard points to secure equipment, electrical power, and access to the outside environment. Should the decision be made for SOFIA to accommodate piggybackers I think it is clear that if only because of the very long lead times required, items one and two would have to be provided as aircraft infrastructure.

Access to the outside environment is somewhat different, as those needs are often specific to individual experiments, whether that access be via a special optical window, or a specialized inlet of the sort needed for the radon daughter measurement installation described earlier. Here I would suggest that, as was done aboard the DC-8 and other research aircraft, that a number of window openings aboard SOFIA be reinforced and modified to take either a window blank or aluminum blanks, which could be chosen and modified as necessary for individual experiments. (One step beyond this that might be taken would be to provide a common inlet manifold, for gas sampling.) Again, because of the long lead-time required (as well as economies of scale) I think it is clear that these facilities would have to be provided as infrastructure.

These modifications will be expensive. That fact, together with the severe time and budgetary constraints facing SOFIA means that a substantial portion—perhaps all—of the associated costs may have to be covered by other sources within NASA, or within the larger atmospheric sciences funding community.

I would argue that this would be a good investment. It's well and good to talk about innovation; what is needed is to provide circumstances in which it can occur (c.f. Little, 2003). While, clearly, the KAO was not the "only game in town"—there are other, well-established "channels" that permit the development of new instruments and the making of atmospheric observations—those tend to require more time to put in place, and involve higher levels of funding and administrative support. While at the time the KAO may have been relatively underused, given the modeling community's continuing and growing need for suitable observational data, and the diminishing opportunities for flight aboard traditional research aircraft, piggybacking aboard SOFIA could be an important, cost-effective resource for the atmospheric science community.

Taming the SOFIA procedural environment.

As discussed at the 2004 workshop (Jenniskens, et al., 2004) a key difficulty facing potential SOFIA piggybackers is the significantly greater cost anticipated for the design, the gaining of approval, and the installation of experimental equipment aboard SOFIA relative to those costs associated with similar installations aboard the KAO—or, for that matter, aboard dedicated research aircraft such as NASA's DC-8. These greater projected costs—perhaps an order of magnitude greater than those that might be encountered for a similar installation aboard the KAO or DC-8—are anticipated not so much because of a higher standard of airworthiness associated with the SOFIA—as was made clear in the preceding discussion, the requirements to fly equipment aboard the KAO were also quite rigorous—or because of any intrinsic mechanical or aerodynamic difference between the C-141 and 747 platforms, but rather because SOFIA will be operated by an outside for-profit contractor, under FAA (Federal Aviation Administration) regulations and procedures.

Thus it is anticipated/feared that the certification process for piggyback experiments aboard SOFIA could prove to be less of an evolving dialog between engineers, as was the case aboard the KAO (or aboard NASA research aircraft such as the ER-2 and DC-8), and more of a formal, crystallized exchange of documents between administrative offices.

Or perhaps not. Whether the actual procedures will prove to be so restrictive remains to be seen, and will depend not only upon the formal administrative aspects (e.g., operating under FAA regulations and procedures) but also upon subjective considerations such as budgets and charges, the level of staffing and the skills and facilities available—as well as the instructions sent down by higher management.

Clearly the immediate and imperative goal of the SOFIA management and operations teams is to get the plane flying and the astronomy program safely underway, within the constraints of the present schedule and budget. However once those goals have been met my hope is that while it is a given that airworthiness standards would continue at their present high levels, still potential piggybackers would encounter a little more suppleness in the certification and installation procedure than is presently anticipated. As an experimenter who in years past has accomplished a lot aboard the Kuiper Observatory, I would very much hope so!

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